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Planetary Atmospheres, Dynamics

Michael Allison

Planetary atmospheres are the circulating fluids of world-sized thermodynamic engines. Their observed wind and wave motions are the dynamic response to differential heating imposed by their absorbed solar radiation and, in the case of the giant outer planets, to the internal energy generated by their formative gravitational contraction. Although partly derived from the observational and analytical tools of astronomy, the comparative study of dynamic atmospheres has emerged as an extension of terrestrial meteorology to the rich variety of size, rotation, mass, temperature, and composition exhibited by the other planets in the solar system. The subject has begun to mature only over the past two decades, largely as a result of the preliminary reconnaissance of the planets by spacecraft. Although based on well-understood laws of mechanics, thermodynamics, chemistry, and radiation, the aggregate behavior of these macroscopic systems has proven outstandingly difficult to deduce and predict. There is as yet no general theory of atmospheric dynamics that can comprehensively account for the observed features of extraterrestrial wind patterns. Some progress has been made, however, in diagnosing the basic physical balances and kinematics. Aside from the challenge to solve individual problems of fascinating complexity, the comparative investigation of motions in planetary atmospheres proceeds with the expectation of eventually attaining a fundamental improvement in the unified understanding of geophysical fluid dynamics.

PARAMETERS AND SCALING RELATIONSHIPS

The dynamics of planetary atmospheres is characterized by the combined effects of rotation, stratification, and dissipation. Although model representations typically require sophisticated mathematics and computation, important insights may be derived from the consideration of simple measures of the relevant parameters and scaling estimates of the force balances. One of the most fundamental constraints on the large-scale motions of a rapidly rotating atmosphere is the approximate balance between horizontal gradients in pressure and the Coriolis acceleration. As discovered in the nineteenth century by Gaspard Gustave de Coriolis, any moving object, such as a cannon ball or a puff of air, traversing a certain horizontal distance will experience a deflection at right angles to its course, as measured with respect to the surface of the planet turning beneath it. The effect may be witnessed as the slow rightward turning, in the northern hemisphere, of the swinging plane of a Foucault pendulum, with a complete period equal to one-half the planetary rotation period, divided by the trigonometric sine of the local latitude, or $\tau_{pend} = \tau_{rot}/2 \sin \lambda$. The corresponding angular rotation frequency $f = 2\pi/\tau_{pend}$, is called the Coriolis parameter or planetary vorticity.

The time required for an atmospheric parcel moving with a speed U to traverse a horizontal distance L is just L/U. Planetary rotation will significantly affect the motion if the corresponding inertial acceleration U^2/L is small compared to the Coriolis acceleration, given as $f \cdot U$. The ratio of inertial to Coriolis acceleration is measured by the Rossby number,

$$\mathrm{Ro} \equiv U/fL,$$

after the pioneering twentieth-century meteorologist Carl-Gustaf Rossby. For large-scale motions at mid-latitudes in the Earth's atmosphere, for example, $\mathrm{Ro} \approx 0.1$. Wherever the Rossby number is small (and viscous effects can be neglected), horizontal gradients in pressure are in approximate *geostrophic* balance with the Coriolis acceleration of the flow. As a result, low-pressure centers are observed as cyclonic weather patterns, locally rotating in the same direction as the planet, whereas high-pressure centers are anticyclonic. Where the Rossby number is large, the Coriolis acceleration is negligible and steady motions represent a balance between horizontal pressure gradients and the centripetal acceleration associated with the flow curvature. Examples of this so-called *cyclostrophic* regime include tornados and the winds of Venus.

The thinness of planetary-scale dynamics, as measured by the small ratio of the characteristic vertical and horizontal scales of the motion, $D/L \ll 1$, generally insures that the vertical pressure gradient in the atmosphere is "hydrostatically" balanced by the weight per unit volume at a given level. (Violent updrafts in localized storm systems and perhaps also deep convective motions in the atmospheres of the giant planets are exceptions for which the vertical acceleration must also be taken into account.) When combined with the equation of state relating the atmospheric pressure to the product of the density and temperature, hydrostatic balance yields the barometric law for the vertical (exponential) drop of pressure with altitude. The associated pressure scale height is given as $H = RT/g$, where R is the gas constant for the mixture, itself fixed in inverse proportion to the mean molecular weight, T is the temperature, and g the gravitational acceleration.

Under special circumstances the atmospheric structure may be regarded as *barotropic*, with constant-density (or isopycnic) surfaces parallel to the constant-pressure (or isobaric) surfaces, for which the horizontal motion is constant with altitude and effectively is decoupled from the thermodynamics. More generally, however, planetary atmospheres exhibit *baroclinic* structure, with isopycnals inclined to the isobars, for which the motion is vertically sheared. In this case the hydrostatic pressure balance, together with the equation of state and the geostrophic (or cyclostrophic) balance of horizontal gradients, prescribe the thermal wind shear. The corresponding scaling relation for the horizontal velocity is

$$U \sim \begin{cases} -(gD/fL)(\Delta T/T), & \text{for Ro} \ll 1, \\ \pm\sqrt{(gD\,\Delta T/T)}, & \text{for Ro} \gg 1, \end{cases}$$

where D denotes the depth of the vertically sheared motion, typically at least as large as the scale height, ΔT is the horizontal contrast in temperature, and again g is the gravitational acceleration, f the Coriolis parameter, L the horizontal scale of the motion, and T the absolute temperature. In the geostrophic ($\mathrm{Ro} \ll 1$) case, the correct sign for the thermal contrast requires that for a positive Coriolis parameter, the velocity U be directed 90° to the right of the direction of decreasing temperature. In the cyclostrophic ($\mathrm{Ro} \gg 1$) case, the sign of the flow velocity is undetermined, except by the further consideration of its forcing. In both cases, the application of the thermal wind balance to the zonal motion breaks down at the equator, where the Coriolis and (zonal) centripetal accelerations vanish. Although extremely useful for the diagnostic inference of horizontal motions from remotely sensed temperature gradients, the thermal wind equation is by itself insufficient to describe the causal establishment or time-evolution of the circulation.

In addition to the horizontal gradients in temperature, the dynamics of an unevenly heated atmosphere inevitably entails the consideration of its vertical stratification. Most of the incoming sunlight is absorbed either at the surface or, in the case of a thick atmosphere, within a deep cloud layer. The resulting excess heat is reradiated at infrared wavelengths, for which the atmosphere is largely opaque, and must be carried by rising motions up to the emission level, where it can be cooled efficiently to space. Rising parcels cool as they expand in equilibration with the decreasing pressure of their ambient environment. For neutrally stable conditions, the drop in temperature with altitude, the so-called lapse rate, is just sufficient to match the cooling of an adiabatically rising parcel (similar to that prescribed by the Schwarzschild criterion for the onset of convection in stars). The static stability is measured as the difference between the adiabatic lapse rate, given as the ratio of the gravitational acceleration to the specific heat at constant pressure ($\Gamma_{ad} = g/c_p$), and the ambient lapse rate Γ. (In the presence of moist convection or other phase changes, the adiabat must also take account of latent heat and variations in molecular weight.) At the top of the convective troposphere, the stability is very nearly the same as Γ_{ad} and increases aloft. Within the troposphere, the weaker but still generally stable stratification, with respect to large-scale motions, depends upon a complicated interplay of radiation, chemistry, and dynamical transports. Although the internal heating within the deep atmospheres of Jupiter and Saturn might support a negative static stability, it is presumed that convective transports will efficiently adjust this to a value nearly indistinguishable from zero. For rapid, nearly adiabatic motion within a statically stable atmosphere, the conservation of heat demands that temperature fluctuations δT balance the associated vertical displacement δz in proportion to the stability, so that

$$\delta T \sim -\delta z \cdot (\Gamma_{ad} - \Gamma),$$

again in the sense that rising motions are cooled.

For geostrophic motion there is a further constraint on the evolution of the flow, given by the conservation of vorticity. Assuming negligible dissipation, this specifies that the change in the rotation or vorticity of the motion is balanced by the vertical stretching of the fluid. Estimating the characteristic scale of the vorticity as the incremental change in velocity δU over a horizontal length L, and expressing the stretching in terms of the vertical displacement, the corresponding scaling relationship is

$$\delta U/L \sim f(\delta z/D).$$

Assuming that the geostrophic ($\mathrm{Ro} \ll 1$), vorticity-conserving motion is coupled to the stratification according to the heat equation, with $\delta U \sim U$ and $\delta T \sim \Delta T$, these may be eliminated from the three balance relations reviewed previously to infer the associated horizontal "deformation" scale, given as

$$L^2 \sim L_D^2 \equiv [g(\Gamma_{ad} - \Gamma)/T] \cdot D^2/f^2.$$

L_D is called the Rossby radius of deformation and represents the characteristic horizontal scale for geostrophic baroclinic motion. For the midlatitude troposphere of the Earth, for example, L_D is approximately 1000 km.

The size and form of dissipation in planetary atmospheres are more difficult to quantify than the inertial and thermodynamic balances. On the time scales appropriate to observed large-scale weather patterns ($\sim L/U$), the motions are effectively inviscid and generally adiabatic. Nevertheless, dissipation plays an essential role

Table 1. Dynamical and Meteorological Parameters for Planetary Atmospheres

	Earth	*Mars*	*Venus*	*Titan*	*Jupiter*	*Saturn*	*Uranus*	*Neptune*
Equatorial radius (km)	6,378	3397	6051	2575	71,490	60,270	25,560	24,760
Rotation period (h)	23.93	24.62	5832 (243 days)	382.7 (15.9 days)	9.925	10.66	17.23	16.12
Axial obliquity (°)	23	25	177	—	3	27	98	30
Emission temperature (K)	255	210	229	85	124	95	59	59
Surface (or cloud) temperature (K)	288	214	731	94	(NH_3) 152	(NH_3) 156	(CH_4) 80	($CH_4 + H_2S$) 80–120
Pressure (bar)	1.013	0.007	92	1.5	0.7	1.4	1.2	1–3
Gravity (m s^{-2})	9.8	3.7	8.9	1.4	24	10	8.8	11
Scale height (km)	8	11	16	20	20	40	30	30
Adiabatic lapse rate (K km^{-1})	9.8	4.4	10	1.3	2.0	0.7	0.8	0.8
Radiative cooling time (s)	$\sim 10^7$	$\sim 10^5$	$\sim 10^7 \times (p/\text{bar})^{1.3}$	$\sim 10^9$	$\sim 10^8$	$\sim 10^9$	$\sim 10^{10}$	$\sim 10^{10}$
Horizontal motion scale (km)	1000	600	6000	3000?	2,000	3,000	8,000?	7,000?
Jet speed (m s^{-1}) midlatitude	+15	+30	+90	+80?	±50	±100	+200	+200?
equatorial	−4	?	+100	+?	+120	+500	−100	−400

in the steady (or time-averaged) equilibration of the flow in response to the continual input of solar energy. Near the lower solid surface of terrestrial-type atmospheres, the dissipation of momentum by small-scale eddies appears to act analogously to friction, and supports a boundary layer of turbulent motions and strong vertical shear. Thermal damping occurs over a characteristic radiative "cooling time," given in proportion to the pressure p and temperature T at a given level as

$$\tau_{rad} \sim pT / \Gamma_{ad}\sigma T_e^4,$$

where T_e is the atmospheric temperature at the infrared emission level, and $\sigma = 5.67 \times 10^{-5}$ mW m^{-2} K^{-4} is the Stefan–Boltzmann constant. Some dissipation of both momentum and heat may occur at high stratospheric levels, as a result of mixing by vertical wave propagation. In addition, significant horizontal mixing may be imposed by unstable eddies in the zonal flow, but probably cannot be described accurately as viscous dissipation and so must be either parametrized or explicitly calculated as nonlinear, small-scale motions.

OBSERVATIONS AND THEORIES

Table 1 summarizes the most essential external parameters for the dynamic planetary atmospheres in the solar system including Saturn's large satellite Titan, along with observational estimates of the characteristic length and velocity scales for their global motions. Although each dynamic atmosphere is unique, certain pairs exhibit sufficient similarity for comparative discussion.

Earth and Mars: Cyclone Engines

The atmospheric dynamics of the Earth is obviously the best studied of all the planets and constitutes a fundamental paradigm for general circulation studies. Its zonal motion is characterized by a "westerly" midlatitude jet in each hemisphere, strongest at upper tropospheric levels, and at low latitudes the weak easterly "trade winds," as discovered by the early transoceanic explorers. (Terrestrial meteorologists customarily label the winds by the direction from which they flow, so that an "easterly" wind blows westward.) The characteristic speeds for the Earth's zonal winds given in the table refer to annual averages at the 500-mbar level, as measured by airborne radiosondes. As early as 1686 Edmond Halley identified the Sun as the ultimate cause of atmospheric motions. In 1735 George Hadley proposed that the preferential heating of low latitudes would drive a slow meridional circulation, rising at the equator and sinking toward the poles, and that returning low-level flow would be rotationally deflected to the west as observed, with an associated surface torque necessarily compensated by eastward flow at higher latitudes.

Although Hadley's proposal proved to be a qualitatively correct picture for the tropical circulation (which bears his name), it did not account for the observed latitudinal gradients in pressure and is now known to be mediated by a reverse meridional circulation at midlatitudes, as suggested by William Ferrel in the nineteenth century. Ferrel demonstrated that the midlatitude winds were geostrophically balanced by the pressure field, with a surface maximum at the descending branch of the Hadley cell, near 30° latitude, and a minimum near the pole. The associated equator-to-pole temperature contrast is about 40 K, as required by thermal wind balance for the midlatitude jet, over a vertical scale of about one scale height. This balance is, however, unstable to longitudinal eddy fluctuations and, as originally proposed by Vilhelm Bjerknes in 1937, gives rise to the pattern of traveling cyclones displayed on synoptic weather maps. Instability theory, as developed by Jule Charney and E. T. Eady in the late 1940s, suggests that the characteristic horizontal scale of the unstable eddies is about four times the deformation scale, or $4L_D \approx 4000$ km. This is observed as the characteristic horizontal spacing of pressure centers, vividly apparent in photographs of the Earth from space as the typically "wave-6" pattern of cyclonic (low-pressure) cloud swirls, encircling the planet at midlatitudes. In the 1920s, even before the unstable origin of the cyclones was understood, Albert Defant had proposed that they transfer heat poleward and restrict the upper-level wind strength, whereas Harold Jeffreys suggested that they are also responsible for the poleward transport of angular momentum required to maintain the surface westerlies against viscous dissipation. Modern computer simulations demonstrate that the general circulation represents an elaborate nonlinear balance of meridional flow and eddy transports of both heat and angular momentum against dissipation, complicated by the radiative and latent heat effects of clouds.

Mars is about half the size of the Earth, but has nearly the same rotation period and axial obliquity. The surface pressure of its thin carbon dioxide atmosphere is less than 1% that of the Earth's but is nevertheless sufficient to support a rich variety of weather phenomena, as revealed by orbiter and lander spacecraft. The radiative cooling time is only about three days and, as a consequence, diurnal variations in temperature are extreme, varying by as much as 60 K. The alignment of the elliptical orbit of the planet with its seasonal solstices produces a hemispheric asymmetry in the evaporation and sublimation of its polar caps, attended by a regular but extreme variation in the surface pressure from about 7 mbar in the northern summer to 9 mbar in the winter. The seasonal meridional mass flow produces a cross-equatorial Hadley circulation, rising in the summer subtropical latitudes and sinking to the other side of the equator. The summer season at the locations of the Viking landers has a monotonously repetitive weather pattern, with upslope winds during the afternoon and downslope winds during the early morning. The spacecraft observations for the northern hemisphere winter, however, suggest a peculiarly bimodal behavior: In some years, this season is characterized by a strong westerly jet, with intense but regular traveling weather fronts. In other years, planet-encircling dust storms develop, extending up to 50 km altitude, accompanied by an intensified Hadley circulation. The first of these appears to be analogous to the terrestrial baroclinic cyclone regime. The midlatitude deformation scale may be estimated from the parameters in Table 1 as $L_D \approx (g\Gamma_{ad}/2T)^{1/2}H\tau_{rot}/2\pi \approx 960$ km. Then, assuming the wavelength of the eddy cyclone pattern is again $4L_D$, and assuming a midlatitude circumference of $\sqrt{2}\pi a$ (where a is the planetary radius), the zonal wave number for baroclinic disturbances may be estimated as $\sqrt{2}\pi a/4L_D \approx 4$, in good agreement with that inferred from the analysis of pressure and wind data at the Viking landers. The global dust storm regime, occurring in occasional northern winters, near the time of perihelion, is perhaps the most remarkable feature of the martian meteorology. This undoubtedly involves some feedback between the radiative heating of the airborne dust, intensified horizontal thermal gradients and winds, and the resulting injection of more dust within the increasingly turbulent surface layer. This is an important problem for further investigation by modeling and spacecraft observations, and may serve as a safe and natural laboratory for the study of "nuclear winter" conditions.

Venus and Titan: Windy Overdrives

Venus is nearly the same size and density as the Earth and, although it intercepts about twice as much sunlight in its closer orbit to the Sun, the high reflectivity of its globally pervasive, high-altitude cloud deck gives it a slightly lower emission temperature. The Venus clouds are composed of sulfuric acid, condensed at an altitude of 65 km, and overlie a thick carbon dioxide atmosphere with a surface pressure of 92 bar and a corresponding "greenhouse" temperature of 730 K. Perhaps the most extraordinary feature of the atmosphere is its zonal superrotation, as measured by the tracking of ultraviolet cloud features in the orbiter imaging data and corroborated by the Doppler radio tracking of several descent probes. The motions amount to about 100 m s^{-1}, with global cloud patterns traveling completely around the planet in 4–5 days, in the same direction but some 50 times as fast as its own (243-day) sidereal rotation. The large Rossby number (~ 50) implies that the motions are in global cyclostrophic balance with the (remotely sensed) temperature field, which indicates a gradual reduction in the wind speed with altitude above the cloud deck. The superrotation represents an excess of angular momentum, as compared with that conserved by meridional motions in the absence of forcing. The excess must be supplied either externally by solar thermal tides or somehow internally by the viscous torque of the planet itself. Although the radiative cooling time near the surface is about 100 yr, at the cloud deck, near the 50-mbar level, it is comparable to the atmospheric rotation period and therefore plausibly supports the efficient diurnal pumping of Sun-following waves, which might provide the requisite momentum driving. According to the celebrated proposal by Peter Gierasch, the superrotation might alternatively be maintained by a global Hadley circulation, which vertically redistributes the viscous torque imposed on its lower branch by the planet's surface, assuming a strong eddy-diffusive transfer of angular momentum aloft from high to low latitudes. Although the Gierasch mechanism assumes an anisotropic mixing of momentum and a negligible mixing of heat, these requirements might be satisfied by "barotropic" eddies arising from horizontal shear instabilities in the global motion field. This idea is consistent with the estimated inefficiency of baroclinic eddy motions, given the largeness of the baroclinic deformation scale at the stable cloud-top levels, in comparison with the planetary radius, due to the slow planetary rotation. The details of the angular momentum mixing are not as yet understood, however, and might also involve some transfer by vertically propagating gravity waves.

Titan is the large satellite of Saturn, about $1\frac{1}{2}$ times the size of the Earth's moon. It has a nitrogen atmosphere, with a surface pressure of 1.5 bar, enshrouded with a thick hydrocarbon haze. The satellite is presumed to be tidally locked to Saturn, with a rotation period equal to its approximately 16-day orbital period. Although the absence of discrete cloud features has prevented the direct tracking of winds on Titan, some tentative information about the motions has been inferred from Voyager infrared measurements of latitudinal variations in the atmospheric brightness temperatures. These imply an equaltor-to-pole contrast of about 20 K at stratospheric levels (~ 1 mbar) and of about 2 K in the lower troposphere (around the 1-bar level). Assuming cyclostropic balance, as appropriate for the slow planetary rotation, and a characteristic flow depth of one scale height, the thermal wind relation implies a zonal velocity of $U \sim \sqrt{(gH\Delta T/T)} \approx 80$ m s^{-1} at upper levels and about 20 m s^{-1} below. Both estimates are consistent with a large Rossby number, as required for cyclostrophic balance, and suggest that Titan may represent a superrotational regime analogous to Venus. If this inference is borne out by further spacecraft observations, it will support a view that atmospheric superrotation is a robust feature of slowly rotating, differentially heated planets.

Jupiter and Saturn: Banded Giants

Jupiter and Saturn are each about 10 times the size of the Earth and rotate over twice as rapidly. Both emit about twice as much energy as they absorb, implying internally heated and deeply convective interiors. Although they differ in their axial tilt, gravitational potential, emission temperature, and visual contrast, the two hydrogen–helium gas giants appear to have qualitatively similar flow regimes. Both planets have high-velocity superrotating equatorial currents and at high latitudes an alternating, axisymmetric pattern of counter-flowing jet streams, as revealed by the longitudinal drift rate of their ammonia clouds. On Saturn, however, the currents are stronger, with equatorial and midlatitude velocities of about 500 and 100 m s^{-1}, respectively, as compared with 120 and 50 m s^{-1} at low and midlatitudes on Jupiter. (The frame of reference for wind velocities on the giant planets is provided by the radio measurement of the rotation of their magnetic fields, presumably tied to their deep interiors.) The predominantly axisymmetric character of the motions on both planets is emphasized by the visually prominent banding of their cloud features. On Jupiter the bright so-called zones generally correlate with regions of anticyclonic shear on the equatorial sides of the prograde jets, flanked by the darker cyclonic "belts." On Saturn the correlation of cloud brightness variations with the motions is more obscure. On both planets, however, infrared measurements indicate that the anticyclonic regions are relatively cool over their cloud tops, plausibly as a result of rising motions, whereas the cyclonic regions are relatively warm. The associated thermal wind shear implies a reduction of the cloud-top winds with altitude. In addition to the zonal cloud bands, the giant planets also show localized regions of swirling motion, or vorticity, such as Jupiter's Great Red Spot.

Unlike the bright synoptic-scale cloud swirls in the Earth's atmosphere, however, most of these tend to be anticyclonic against the planetary rotation.

Although the large-scale motions of Jupiter and Saturn are characterized by small Rossby numbers, comparable to that for midlatitude winds on the Earth, the multiplicity of the jets and the superrotational equators clearly represent a radically different dynamical regime. The differences are probably related in some way to the deep stratification. Unlike the terrestrial planets, the jovian atmospheres have no rigid lower boundaries to support strong horizontal pressure contrasts and are heated from below over depths of several scale heights. The depth of the zonal motion itself is a fundamental uncertainty. According to one view, the observed cloud-top winds extend throughout the molecular hydrogen envelope on convective cylinders of motion, concentric with the planetary spin axis. Alternatively, the motions might be confined to a shallow thermal wind layer, supported perhaps by thermal gradients associated with a latitudinally-variable water cloud, some 2–5 scale heights below the ammonia deck. Whatever the depth, the observed velocities appear to relate to the spacing of the jets according to

$$U \sim \beta \cdot L^2,$$

where $\beta \equiv 4\pi(\cos\lambda)a\tau_{\rm rot}$ is the so-called planetary vorticity gradient, with a denoting the planetary radius and $\cos\lambda$ the trigonometric cosine of the latitude. A second relation between velocity and the horizontal motion scale is needed to complete the specification of the dynamics. It is tempting to consider the possibility that the length scale is set by a baroclinic deformation radius L_D, but is difficult to estimate because the static stability at deep levels is unknown, but presumably small, whereas the depth scale D might be as large as several scale heights. It is interesting to note that at upper tropospheric levels on both Jupiter and Saturn the deformation radius may be estimated as $L_D \approx (g\Gamma_{\rm ad}/2T)^{1/2}H\tau_{\rm rot}/2\pi \sim$ 2000 km, comparable to the spacing of the jets. This may be only a coincidence, however, and at any rate is only diagnostic.

Uranus and Neptune: Topsy-Turvy Mysteries

Uranus and Neptune are roughly one-third the size of Jupiter and Saturn but are similarly constituted from predominantly hydrogen–helium mixtures, laced with significant traces of heavier elements. Both are sufficiently cold to effect the condensation of methane, which forms the top of their visual cloud decks. Unlike the other giant planets, Uranus appears to have a negligible internal heat source. Its rotation axis is peculiarly almost coincident with the plane of its orbit, so that on average its polar regions receive more sunlight than its equator, unlike any other planet in the solar system. Elementary reasoning, based on experience with the other planets, anticipates that this reverse solar forcing might induce a reverse meridional circulation, rising at high latitudes and sinking at the equator, along with a retrograde geostrophic wind. The *Voyager 2* observations tentatively indicate that there is indeed a retrograde (approximately 100 m s^{-1}) wind at the uranian equator but, surprisingly, also indicate an even stronger prograde flow (in excess of 200 m s^{-1}) at high latitudes. Neptune is only slightly more massive than Uranus but has a sufficient internal heat source to support almost the same emission temperature, despite its much greater distance from the Sun. Neptune has an upright 30° obliquity so that, as for Jupiter and Saturn, its weak solar forcing must be greatest at the equator. As if to confound further the systematic understanding of the outer planet atmospheres, however, the neptunian winds are if anything more similar to those on Uranus. As revealed by cloud-tracked wind observations during the 1989 *Voyager 2* reconnaissance, the equatorial velocity is 300 m s^{-1} retrograde, gradually diminishing toward the pole, with some prograde flow near 70° latitude, as measured with respect to its radio rotation rate. The dynamical maintenance of the zonal circulation of both planets eludes the grasp of any presently available theory.

FUTURE PROSPECTS

Despite the enormous progress of recent years in the study of planetary atmospheres, it is not yet possible to answer even the most fundamental questions regarding the maintenance of their dynamics and general circulation. The prospects for further observational constraints from the 1993–1995 *Mars Observer*, 1995–1997 *Galileo* (Jupiter), and 2002–2006 *Cassini* (Saturn and Titan) missions are encouraging, however. These will involve extended orbital coverage over several years and, in the case of Jupiter and Titan, the first in-situ measurements by descent probes. As the planetary arrivals of these new spacecraft are patiently awaited, it will be equally important to develop theories and computer models of increasing maturity and imagination.

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See also **Jupiter, Atmosphere; Mars, Atmosphere; Planetary and Satellite Atmospheres; Saturn Atmosphere; Uranus and Neptune, Atmospheres; Venus, Atmosphere.**